UNIVERSITY OF LIVERPOOL

Non-Supersymmetric Heterotic String Classification and Asymmetric Orbifolds

Work in collaboration with Alon Faraggi and Viktor Matyas

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Overview

- Plan for talk:
  - Motivation
  - Free fermionic models.
  - Highlights of $\mathbb{Z}_2 \times \mathbb{Z}_2$ [Faraggi [1]] classification program for $\mathcal{N} = 1$ and $\mathcal{N} = 0$
  - Asymmetric Orbifolds from Free Fermionic Construction
  - Example Cases
  - Some Classification Results
  - One-loop Potential and super no-scale models
  - Conclusions

Motivation: Non-SUSY

- Absence of SUSY signal from LHC
- Problems:
  - Hierarchy Problem
  - CC Problem
  - Instabilities: tachyons, dilaton backreaction...
  - Moduli Stabilisation
  - Gauge Coupling Unification

Motivation: Asymmetric Orbifolds

- ⋆ Realise non-geometric string vacua [Narain et al; Antoniadis et al; Kawai et al; Plauschinn; Groot Nibbelink et al; [2, 3, 4, 5, 6, 7]]
- ⋆ Pheno. features [Faraggi [8, 9, 10, 11]]
  - ⋆ Early realistic free fermionic models asymmetric [Faraggi et al [12, 13]]
  - ⋆ Fixing Geometric Moduli
  - ⋆ Doublet-Triplet Splitting
  - ⋆ Untwisted Top quark mass coupling
  - ⋆ Hierarchical Top-bottom quark mass splitting
  - ⋆ Models with vanishing one-loop CC [Kumar et al; Angelantonj, et al; Harvey; Shiu,Tye; Sugawara et al; [14, 15, 16, 17, 18, 19]]

Free Fermion Construction I

- ⋆ Worldsheet CFT construction of heterotic string defined at enhanced symmetry point in moduli space [Antoniadis et al; Kawai et al [3, 4, 5]]

- ⋆ $D = 10 \implies$ introduction of free fermions on worldsheet

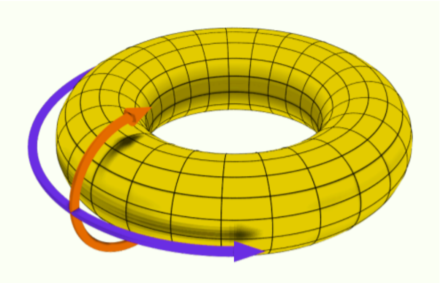
$$\{\underbrace{\psi^{\mu=1,2}, \chi^{i=1,\dots,6}}_{\substack{\text{S'partners of } X^\mu \\ (\chi\text{'s compact in 4D})}} \,||\, \underbrace{\bar{\psi}^{1,2,3,4,5}, \bar{\eta}^{1,2,3}}_{\substack{\text{rank 8} \\ \text{Observable G. G.}}}, \underbrace{\bar{\phi}^{1,2,3,4,5,6,7,8}}_{\substack{\text{rank 8} \\ \text{Hidden G. G.}}}\} \tag{1}$$

- ⋆ Reduction to $D = 4 \implies$ introduction of

$$\{y^i, w^i \,||\, \bar{y}^i, \bar{w}^i\}, \quad i = 1, \dots, 6 \tag{2}$$

$\longleftrightarrow T^6$ fermionised coordinates: $i\partial X^i_L = y^i w^i$.

Free Fermion Construction II



- PF: $Z_f \sim \sum_{\alpha,\beta} C\left[\begin{smallmatrix}\alpha\\ \beta\end{smallmatrix}\right] Z\left[\begin{smallmatrix}\alpha\\ \beta\end{smallmatrix}\right]$
- Model defined by:
  - Basis vectors $\mathscr{B} \ni \mathbf{v_i} = \{\alpha(f_1), \alpha(f_2), \ldots, \alpha(f_n)\}$
  - GGSO phases: $C\left[\begin{smallmatrix}\mathbf{v_i}\\ \mathbf{v_j}\end{smallmatrix}\right]$.

Symmetric $\mathcal{N} = 1\ \mathbb{Z}_2 \times \mathbb{Z}_2$ Classification Highlights

$SO(10)$ [Faraggi, Rizos, Nooij [20]]:

Spinor-Vector duality: $\#(\mathbf{16} + \overline{\mathbf{16}}) \longleftrightarrow \#\mathbf{10}$ [Faraggi, Rizos, Kounnas et al [21, 22]]

$SO(6) \times SO(4)$: [Assel et al [23]]

Exophobic viable vacua

$SU(5) \times U(1)$: [Faraggi et al [24]]

No exophobic vacua for odd generations

$SU(3) \times SU(2) \times U(1)^2$ & $SU(3) \times SU(2)^2 \times U(1)$: [Faraggi et al [25, 26, 27]]

- ⋆ Viable vacua scarce $\sim \mathcal{O}(10^{-11}) \rightarrow SO(10)$ 'Fertility Conditions'

Symmetric $\mathcal{N} = 0$ $\mathbb{Z}_2 \times \mathbb{Z}_2$ Classification Highlights

- SAT/SMT Solvers aid in classification [Faraggi,Percival et al [28, 29]]
- CC Distributions, misaligned SUSY [Dienes; Angelantonj et al; Cribiori et al; [30, 31, 32, 33]] and 'super no-scale' models [Kounnas,Partouche; Coudarchet et al [34, 35, 36]]

$SO(16) \times SO(16)$-Derived: [Dixon, Harvey; Seiberg, Witten; Alvarez-Gaumé et al [37, 38, 39]]

- Gravitino projected by GGSO phase [Ashfaque et al; Abel et al; Faraggi, et al [40, 41, 42]]
- Scherk-Schwarz can be implemented

Tachyonic-Derived: [Faraggi, Matyas, Percival [42, 43, 44, 45]]

- Tachyon-free in 4D
- Explicit SUSY breaking
- No intermediate GUT Higgs except $SU(3) \times SU(2) \times U(1)^2$

Towards Asymmetric Classification: the NAHE Set

[Faraggi, Nanopoulos [46]]

- To ensure there's an R and NS sector for M.I.

$$\mathbb{1} = \{\text{all Ramond}\} \tag{3}$$

- SUSY generator ($\mathcal{N} = 4$)

$$S = \{\psi^\mu, \chi^{1,\dots,6}\} \tag{4}$$

- $\mathbb{Z}_2 \times \mathbb{Z}_2$ twists s.t. $\mathcal{N} = 4 \to 1$

$$\begin{aligned} b_1 &= \{\psi^\mu, \chi^{12}, y^{34}, y^{56} \mid \bar{y}^{34}, \bar{y}^{56}, \bar{\psi}^{1,\dots,5}, \bar{\eta}^1\}, \\ b_2 &= \{\psi^\mu, \chi^{34}, y^{12}, w^{56} \mid \bar{y}^{12}, \bar{w}^{56}, \bar{\psi}^{1,\dots,5}, \bar{\eta}^2\}, \\ b_3 &= \{\psi^\mu, \chi^{56}, w^{12}, w^{34} \mid \bar{w}^{12}, \bar{w}^{34}, \bar{\psi}^{1,\dots,5}, \bar{\eta}^3\}. \end{aligned} \tag{5}$$

- Untwisted G.G. $SO(10) \times SO(6)^3 \times SO(16)$

Geometric Moduli

- NAHE Set moduli space

$$\left(\frac{SO(2,2)}{SO(2)\times SO(2)}\right)^3 \qquad (6)$$

$(T^1, U^1),\ (T^2, U^2),\ (T^3, U^3)$

- Marginal operators generating Abelian Thirring Interactions [Chang, Kumar [47]]

$$J_L^i(z)\bar{J}_R^j(\bar{z}) =: y^i w^i :: \bar{y}^j \bar{w}^j := \begin{cases} (i,j=1,2) \\ (i,j=3,4) \\ (i,j=5,6) \end{cases} \qquad (7)$$

- $\longrightarrow$ Asymmetric BCs of $\{y^i, w^i \,||\, \bar{y}^i \bar{w}^i\}$ can project moduli! [Faraggi [8]]

$SU(5) \times U(1)$ and Asymmetric Pairings

[Based on work: Faraggi, Matyas, Percival 2202.04507 [29]]

- Extra basis vector imposes asymmetric BCs and breaks to $SU(5) \times U(1)$ [Antoniadis et al; Nanopoulos et al; [48, 49]]

$$\gamma = A\left(\{y^{123456}, w^{123456} \,||\, \bar{y}^{123456}, \bar{w}^{123456}\}\right) + \left\{\bar{\psi}^{1,\ldots,5} = \bar{\eta}^{1,2,3} = \frac{1}{2} = \bar{\phi}^{\cdots}\right\} \tag{8}$$

- 6 Symmetric shift vectors

$$e_{i=1,\ldots,6} = \{y^{i}, w^{i} \,||\, \bar{y}^{i}, \bar{w}^{i}\} \tag{9}$$

- Symmetric $\mathbb{Z}_2 \times \mathbb{Z}_2$: e_i's lift degeneracy:

$$3 \times 16 \text{ sectors} \longleftrightarrow 48 \text{ fixed points}$$

Example Cases

Case 1: $\cancel{(T^1, U^1)}, \cancel{(T^2, U^2)}, \cancel{(T^3, U^3)}$

- $A = \{\bar{y}^{36}, \bar{y}^2\bar{w}^5, \bar{w}^{14}\}, \cancel{e_i}$
- Notable model of this type [Faraggi, Matyas, Percival [44]]
- Discussed for Narain orbifolds in, e.g., [Groot Nibbelink, Vaudrevange [7]]

Case 2: $(T^1, U^1), (T^2, U^2), (T^3, U^3)$- all retained

- $A = \{y^{36}, y^1w^6, w^{13}\}, \mathscr{B} \ni e_2, e_4, e_5$

Case 3: $(T^1, U^1), \cancel{(T^2, U^2)}, \cancel{(T^3, U^3)}$

- $A = \{\bar{w}^{34}, \bar{w}^{56}\}, \mathscr{B} \ni e_1, e_2$

Asymmetric Pairings Classification

Untwisted Moduli in each Torus	Odd Number Generations Possible	Frequency
(2, 2, 0)	No	992
(2, 0, 2)	No	992
(0, 2, 2)	No	992
(4, 2, 2)	No	824
(2, 4, 2)	No	824
(2, 2, 4)	No	824
(0, 0, 0)	No	256
(4, 0, 0)	No	244
(0, 4, 0)	No	244
(0, 0, 4)	No	244
(4, 4, 0)	No	200
(4, 2, 2)	Yes	200
(4, 0, 4)	No	200
(2, 4, 2)	Yes	200
(2, 2, 4)	Yes	200
(0, 4, 4)	No	200
(4, 4, 4)	No	146
(4, 4, 4)	Yes	94
(4, 4, 0)	Yes	56
(4, 0, 4)	Yes	56
(0, 4, 4)	Yes	56
(2, 2, 0)	Yes	32
(2, 0, 2)	Yes	32
(0, 2, 2)	Yes	32
(4, 0, 0)	Yes	12
(0, 4, 0)	Yes	12
(0, 0, 4)	Yes	12

Results Case 2

	Total models in sample: 10^9				
	SUSY or Non-SUSY:	$\mathcal{N}=1$	Probability	$\mathcal{N}=0$	Probability
	Total	15624051	1.56×10^{-2}	984375949	0.984
(1)	+ Tachyon-Free			30779240	3.08×10^{-2}
(2)	+ No Observable Enhancements	15135704	1.51×10^{-2}	28581301	2.86×10^{-2}
(3)	+ Complete Generations	15135704	1.51×10^{-2}	28581301	2.86×10^{-2}
(4)	+ Three Generations	89930	8.99×10^{-5}	195716	1.96×10^{-4}
(5)	+ Heavy Higgs	89820	8.98×10^{-5}	129233	1.29×10^{-4}
(7)	+ TQMC	89820	8.98×10^{-5}	129233	1.29×10^{-4}
(8)	+ $a_{00}=N_b^0-N_f^0=0$			388	3.88×10^{-7}

Figure: Results from scan of 10^9 GGSO configurations for phenomenological characteristics allowing for both $\mathcal{N}=1$ and $\mathcal{N}=0$ vacua

Results Case 2: CC Distribution

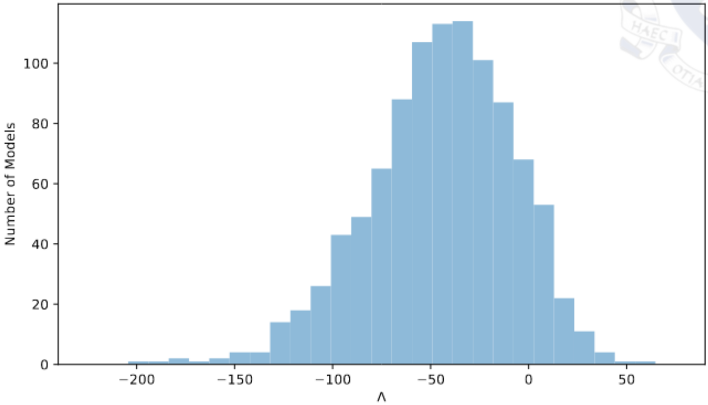


Figure: Distribution of one-loop CC (at FF point) for sample of 10^3 satisfying constraints (1)-(7)

Results Case 3: No 3 Generation Models

Retaining only (T^1, U^1) contradicts 3 $SU(5) \times U(1)$ generations

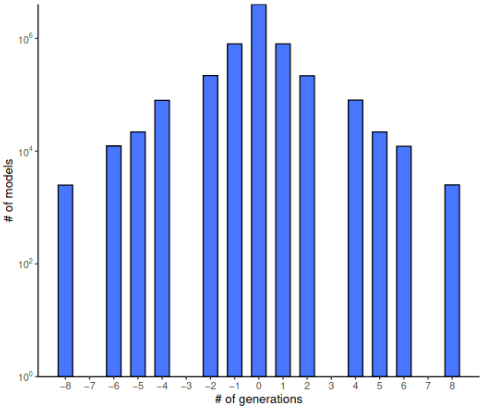


Figure: Distribution of generation number for sample of 10^7 Case 3 vacua

Partition Function

- PF takes schematic form

$$Z_f = \sum_{\text{spin structs.}} (-1)^{\Xi(\dots)} \left(\prod_{f=\psi^\mu,\chi^{12},\chi^{34},\chi^{56}} \theta_f \right) \times \left(\prod_{\bar{f}=\bar{\psi}^{1,\dots,5},\bar{\eta}^{123},\bar{\phi}^{1,\dots,8}} \bar{\theta}_{\bar{f}} \right) \underbrace{\Gamma_{6,6}}_{Z_{y^i,w^i,\bar{y}^i,\bar{w}^i}} \tag{10}$$

- Away from FF point, e.g. Case 3: $\Gamma_{6,6} \rightarrow \Gamma_{6,6}(T^1, U^1)$

One-Loop Potential Case 3

- ⋆ Can realise Scherk-Schwarz in first torus via $\sim (-1)^F \delta_1$ [Florakis, Rizos; Abel et al [50, 51, 52, 41]]

$$m_{3/2} \sim \frac{|U^1|}{\sqrt{\mathfrak{Im}(T^1)\mathfrak{Im}(U^1)}} \sim \frac{1}{R_1} \tag{11}$$

so $R_1 \to \infty \implies m_{3/2} \to 0$

- ⋆ Since ~~(T^2, U^2), (T^3, U^3)~~

$$V_{1-loop}(T^1, U^1) \sim \int \frac{d^2\tau}{\tau_2^3} Z(\tau, \bar{\tau}, T^1, U^1) \tag{12}$$

- ⋆ Super No-Scale models: exponentially suppressed CC [Itoyama, Taylor; Antoniadis [53, 54]] (necessary but not sufficient [Florakis, Rizos [52]])

$$\Lambda \propto (N_b^0 - N_f^0)\frac{1}{R^4} + \mathcal{O}(e^{-\alpha R^2}), \tag{13}$$

Conclusions

- ⋆ Systematic framework with geometric moduli fixing for phenomenological models
- ⋆ No-go results for constraints, e.g. absence of 3 generations, with help from SMT Solver
- ⋆ Can investigate one-loop potential for super no-scale models with constrained moduli.

[The Irregularites of Discernment - Manalo])

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